

HIGH TEMPERATURE SUPERCONDUCTING OPENING PULSER SWITCH WITH  
COMPACT THERMOELECTRIC SOURCE

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Abstract

A high temperature superconducting switch with external magnetic field switching was utilized to switch a thermoelectric source. The superconducting switch was constructed of filaments of Yttrium-Barium-Copper Oxide (YBCO) ceramic and switched with an externally applied magnetic field. The superconducting switch is being used as an opening switch for a thermoelectric current source. The thermoelectric source, based on Seebeck effect, is similar to a thermocouple in operation, and is capable of high current, low voltage generation. It consists of a series of hot and cold junctions, arranged in series to increase the voltage of the system. Source output is a function of temperature differential between cold and hot junctions. The superconducting switch operates at liquid nitrogen temperature. Therefore, liquid cryogen is available to the cold junctions of the current source, and, with sufficient heat applied to the hot junctions, a significant temperature differential, far greater than that obtained using convention cooling, is available, thus increasing the overall efficiency of the system. The device sees application wherever a fast acting, lossless switch or current limiter is required, with a compact, simple power source, neither of which have any moving parts to fail or wear.

Introduction

Electrical energy storage has normally been accomplished by either storing the energy as an electrostatic charge in a capacitor or rotational kinetic energy in a rotating machine. The other component often mentioned for energy storage is the inductor. The usable energy density of an inductor is greater

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than either of the previous two components. However, inductive energy storage systems have yet to be made practical due to the need to interrupt the flow of current in the inductor, which will allow the inductor to discharge. The need for a practical opening switch has prevented the exploitation of this technology.

A type of opening switch often proposed for inductive energy storage is the superconducting switch. The current would be allowed to flow through the superconducting switch, with no losses, and then the switch would be placed into normal conduction, effectively opening. Standard superconducting devices operate at liquid helium temperature (4 K), which adds a great deal of complexity and is thus impractical. The advent of high temperature superconductors, operating at liquid nitrogen temperature (73 K) or above has generated new interest in this technique. An energy storage system consisting of a superconducting switch, a cryogenically cooled inductor and other components using cryogen would be most effective.

A superconducting switch may be opened by increasing its temperature above the critical temperatures of the conductor or by the presence of a magnetic field. The magnetic field required to force a superconductor into normal conduction can be quite small. The self generated magnetic field from the current flowing in the conductor is often sufficient to force the superconductor into normal conduction. This has been a limiting factor in the use of high temperature superconductors in power applications. It also, however, allows an opportunity for control of high temperature superconductors. A magnetic field, applied externally to a superconducting element, can force the element into normal conductivity, creating an opening switch or current limiter.

Illinois Superconductor, Inc. has built a such device, designated a Magnetically Activated Superconducting Switch (MASS). This switch, shown in Figure 1, consists of filaments of Yttrium-Barium-Copper Oxide (YBCO), a Type II high temperature superconductor, suspended in a liquid nitrogen dewar, with terminations to the outside. A copper wire solenoid is mounted coaxially around the YBCO filaments, inside the dewar. When the dewar is filled with liquid nitrogen, both superconductor and solenoid are cooled. A current flow is established in the superconductor and may be reduced or interrupted by application of current to the solenoid, which produces the necessary magnetic field in the superconductor. This magnetic field produces vortices as a consequence of the Meissner effect. Self induced magnetic field due to current in the YBCO filaments also has its effect on limiting current.

We at the Army Research Laboratory saw the potential in this device as an opening switch. We were able to utilize such a device in conjunction with a low impedance thermoelectric power source, as the first step in the construction of an inductor based energy storage system. The thermoelectric device has advantages in being low impedance and utilizing cryogen, in this case liquid

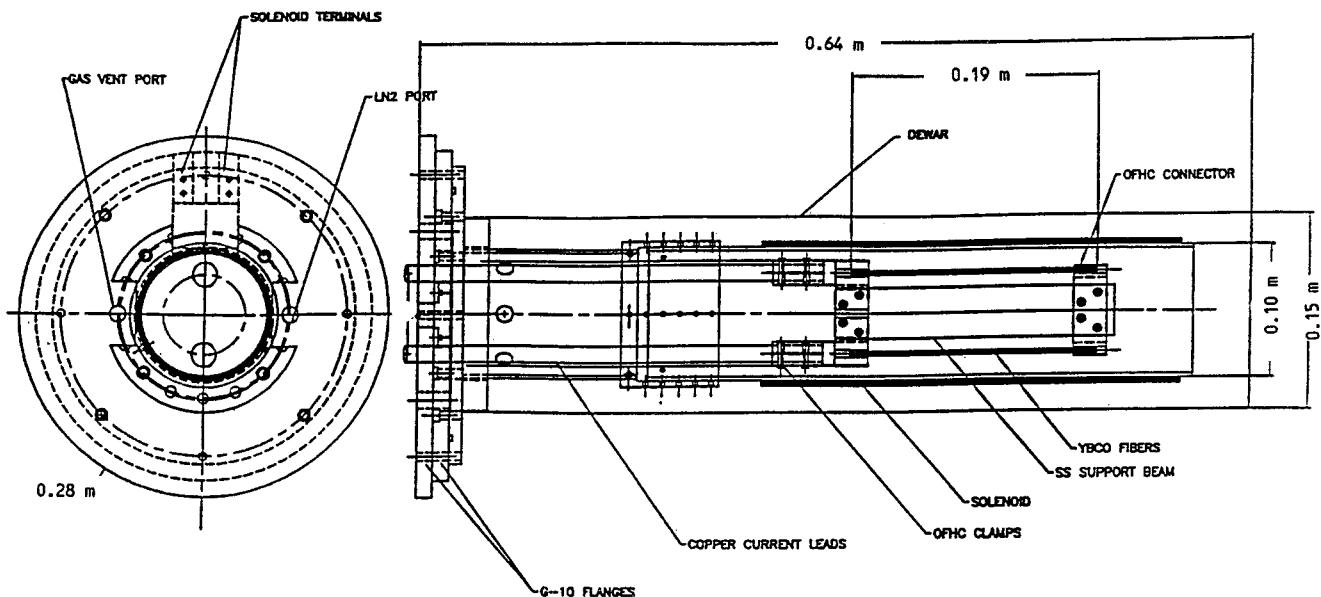


Figure 1. Magnetically Activated Superconducting Switch (MASS). The YBCO filaments forming the switch and the solenoid that generates the controlling magnetic field are mounted coaxially and are placed in a liquid nitrogen dewar, and thus use the same cryogen to operate.

nitrogen, as a means of generating the cold side temperature essential to the operation of this device. This device utilizes the same principle as a thermocouple, only with sufficient voltage

and current to make a power generating device. Thus, cryogenically operating devices may generate the energy, control the energy and, with the addition of an inductor, store the energy.

#### Description of Experiment

A schematic of the experiment is shown in Figure 2. The key elements are the eight YBCO strands mounted coaxially with a solenoid. Two solenoids were used, one with 14 turns, the other with 1050. This permitted the applied magnetic field to be varied. The YBCO filaments form the switch and are supplied power by a thermoelectric device, consisting of eight brass-nickel thermocouples connected in series. Liquid and supercooled gaseous nitrogen established the cold junction temperature of the device. Small electric heaters established the hot junction temperatures, as well as the device's energy source. The temperature differential is on the order of 125 K and, with this differential, currents of 20-30 A are readily produced. The solenoid and thereby the control current is provided via a capacitor discharge, controlled by a thyristor. Currents and voltages are observed at

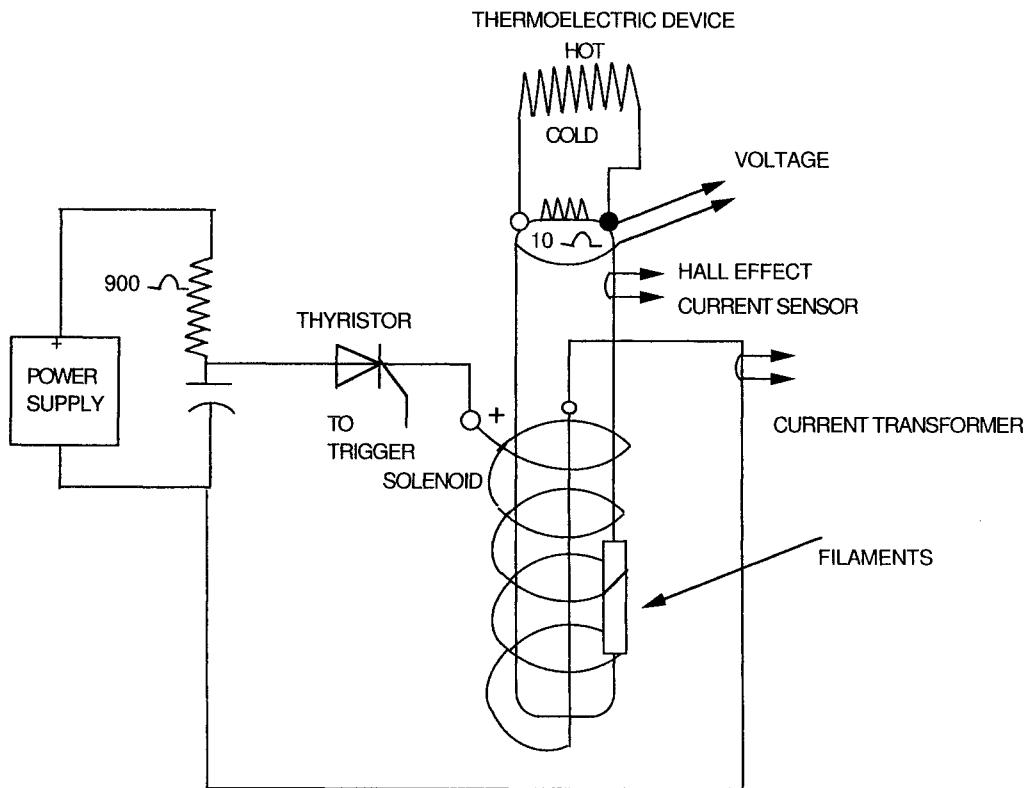


Figure 2. Schematic of experimental apparatus. Current limiter consists of 8 YBCO filaments mounted coaxially within a solenoid control coil. The control coil is excited by capacitor discharge, controlled by a thyristor. A thermoelectric device, shown at the top, consisting of 8 brass-nickel thermocouple pairs, provides experiment power. Voltages and currents are monitored as shown.

the points indicated.

The resistance of YBCO filaments as a function of applied current and applied external magnetic field is shown in Figure 3. Note the relatively benign effect of the self induced magnetic field, arising from the current, with no external magnetic field present ( $B=0$ ). The applied current must reach almost 40 A before an appreciable increase in resistance is noticed. Application of an external field, ranging from 338 to 828 gauss (0.0338 to 0.0828 T) results in a significant change in resistance, resulting in switching or current limiting action.

The external magnetic field was varied in the experiments from 96 to 503 gauss (0.0096 to 0.0503 T). This resulted in current limiting of 12% to 88%, respectively. The best experimental results are shown in Figure 4. Here, the top trace is the applied magnetic field from the solenoid, and is calculated from measured solenoidal current. Peak magnetic field is approximately 0.05 T. The second trace is the superconductor current, which drastically reduces, then returns to its original

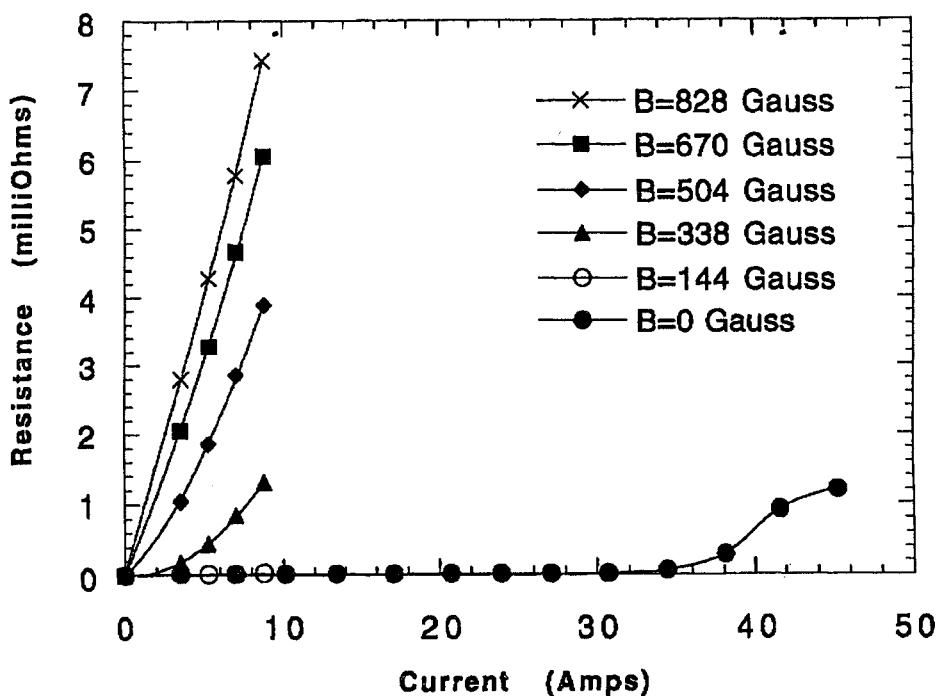


Figure 3. YBCO filament resistance as a function of current and applied external magnetic field. Note that the current must be relatively high to affect resistance and that external magnetic field has a strong effect on filament resistance (see Reference 1).

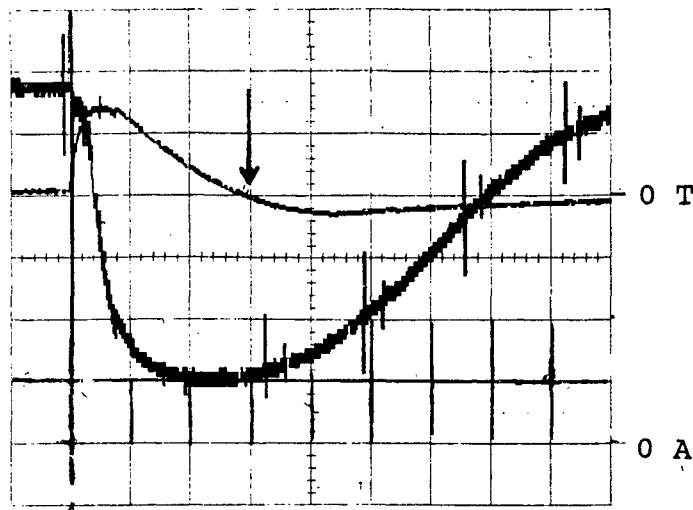


Figure 4. Best experimental results. Top trace is applied magnetic field (0.035 T/ vertical division) calculated from applied solenoid current. The bottom trace is the superconductor field but returns to full current of 11.5 A (2 A/ vertical division) in approximately 25 ms (5 ms/ horizontal division) after cessation of applied external magnetic field (arrow).

filament current, which falls off rapidly with applied magnetic value of 11.7 A in approximately 25 ms after the cessation of the applied magnetic field. The cycle may then be repeated. Note the current fall time is much faster (approximately 2 ms) than the current recovery rise time. This fall time is much faster than

could be obtained by driving the superconductor into normal conduction by raising the temperature. Thus, the delay associated with thermal time constants is avoided, both on fall time and on rise time. The superconductor need not be subjected to rapid warming and cooling, with its attendant delays and the susceptibility of the device to mechanical degradation due to thermally induced stresses to the superconducting material.

### Discussion of Results

The MASS was shown to satisfactorily limit current and this was accomplished by a simple, easily applicable method. The presence of cryogenic material, in this case liquid nitrogen, was exploited in the thermoelectric generator, which provided power for the experiment. This concept may be further expanded to include a cryogenically cooled inductor, thus forming a complete inductor based energy storage system. The YBCO based device

functions more as a current limiter than as a switch. However, operating this type of current limiter in series with a true opening switch, such as solid state device such as Gate Turnoff Thyristor (GTO) or an Insulated Gate Bipolar Transistor (IGBT), the superconducting device could vastly increase the range of solid state devices, which normally can conduct more current than they can turn off. The use of a solid state switch can extend yet again the concept of integrated cryogenic operation, in that the solid state switch can also be cooled cryogenically, for greater efficiency. In any event, none of the technologies described above have any moving parts, so mechanical failure is minimized and wear is essentially eliminated. This greatly adds to the reliability of the device and expands the operating life greatly. This latter point is critical if the system is to be operated in not easily accessible location, such as a space environment. The space environment also normally has cryogen available.

### Reference

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